Measurements of Atmospheric Attenuation on an Earth-Space Path at 90 GHz Using a Sun Tracker

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Measurements of 90-GHz attenuation through the total atmosphere due to absorption by clouds, fog and rain are presented and compared with simultaneous measurements at 16 GHz. It is seen that rain is the most important contributor to atmospheric extinction at 90 GHz, light rain causing greater then 25-dB attenuation on a number of occasions during the measurement period.

I. INTRODUCTION

Absorption in the atmospheric window between the 60-GHz oxygen absorption band and an oxygen absorption line at 118.75 GHz is due to absorption by the tails of atmospheric oxygen and water vapor features. Liquid water, when present in the form of rain, cloud and fog, also causes much attenuation in this atmospheric window. Measurements of attentuation through the total atmosphere are of importance in helping to decide the feasibility of earth-satellite communications in this frequency region.

Measurements of attenuation througb the clear atmosphere as a function of atmospheric water vapor content have been made by F. I. Shimabukuro[1] on an earth-space path at 90 GHz. The results are in fair agreement with theory. A. W. Straiton and C. W. Tolbert[2] and D. C. Hogg and R. H. Turrin[3] have measured propagation loss through the clear atmosphere along ground-based paths at frequencies near 94 GHz. Their results agree satisfactorily with tbeoretical predictions provided suitable values are taken for the pressure broadening constants of the oxygen and water-vapor lines.[4] Hogg and Turrin[3] have also measured attenuation due to rain at 70 GHz along ground-based paths, and the results again show reasonably good agreement with tbeory.[4]

There is however a lack of experimental data on the effects of rain, cloud and fog on attenuation along earth-space paths at frequencies near 90 GHz. Theoretical treatment of the problem is hampered by the lack of detailed knowledge of rain and cloud characteristics. Recent papers by A. E. Freeny and J. D. Gabbe,[5] and R. A. Semplak[6] have discussed rainfall distributions measured in the neighborhood of Crawford Hill, New Jersey, and simultaneous short path attenuation measurements at 18.5 and 30.9 GHz. For the most part, however, little is known about the horizontal and vertical distributions of rain, and even less is understood about those of clouds.

The need for direct measurements of total atmospheric attenuation in this frequency region is thus apparent and it provided the incentive to carry out such measurements recently using the Crawford Hill sun tracker.[7]

II. APPARATUS

A receiver operating at 90 GHz was assembled and calibrated in the laboratory. The sun tracker normally operates at 16 and 30 GHz. For the purpose of this experiment the 90-GHz receiver replaced the 30-GHz receiver. A block diagram showing the receiver connected to the sun tracker can be seen in Fig. 1. Linear and logarithmic chart recorder outputs were available.

The receiver was measured to have a double sideband noise figure of 11.0 dB (i.e., a noise temperature of 3100°K) and a dynamic range of 25 dB when observing the sun.

A noise lamp, coupled into the line via a directional coupler, was calibrated using matched loads at room temperature and liquid nitrogen temperature.

The sun tracker antenna beam at 90 GHz was observed by allowing the sun to drift through it. The result, a convolution of the sun's brightness distribution with the antenna beam pattern, looked quite symmetric and showed no large sidelobes. From this measurement a beamwidth of 25 minutes of arc was computed for the sun tracker at 90 GHz. A similar measurement determined the beam width at 16 GHz to be 65 minutes of arc. Thus, almost the entire solar disc, about 32 minutes of arc, was covered by both beams.

III. MEASUREMENTS

The 90-GHz receiver was attached to the sun tracker during the period from December 2 to 16, 1969. During that time a variety of

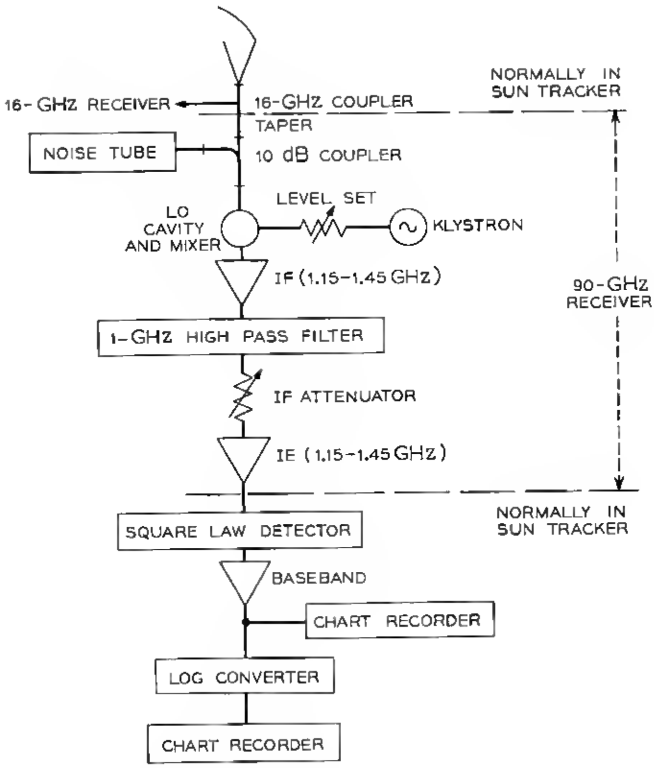

Fig. 1—Block diagram of the 90-GHz receiver in the sun tracker.

weather conditions, viz., cloud, thick fog, rain and some wet snow, occurred at Crawford Hill. The excess attenuation at 90 GHz was measured for all of these. No attempt was made to obtain attenuation statistics. In fact, once the attenuation through the clear atmosphere had been measured and the clear weather levels noted on the chart recorder, the receiver was switched on only during periods of bad weather or when cloud was present; in other words, only when excess attentuation was expected.

A discussion is given of the attenuation at 90 GHz caused by various types of weather conditions. To offset the necessarily qualitative descriptions for most weather conditions (e.g., light cloud, heavy fog, etc.) the excess attenuation at 90 GHz will be compared to that simultaneously measured with the 16-GHz receiver. In this way the 90-GHz data will be seen less as isolated attenuation measurements

due to random weather conditions, and more as results to be viewed in perspective with the more familiar 16-GHz data.

It should be borne in mind that at the time these measurements were made, the sun was very low in the southern sky, its elevation angle varying from about 27° at noon to 15° at 3 P.M. These angles correspond to path lengths through the atmosphere of 2.2 and 4.0 times the path length at the zenith respectively.

Attenuation through the clear atmosphere was measured by observing the intensity of solar radiation versus zenith angle. On a clear cold day (temperature, 32° F; relative humidity, 50%) a value of 0.38 dB was obtained for the attenuation through one atmosphere.

3.1 *Excess Attenuation due to Clouds*

Four basically different types of cloud cover were encountered, the attenuation characteristics of which are summarized in Table I. The values of attenuation were actually measured from the output of the linear recorder, because small dB changes were more easily measured here than on the output of the logarithmic recorder. Only those values of attenuation measured between 10 A.M. and 2 P.M. are quoted in the table. During these times the atmospheric path length took on values between 2.2 and 2.8 times the zenith path length. The maximum attenuation values quoted in the table did not occur at the time of the longest path length for any of the four types of clouds cover.

The measured ratios* of the 90- and 16-GHz cloud attenuations for the first two cloud cases are about what one would expect based on theoretical calculations. From expressions given by D. E. Kerr[8] for attenuation due to small water droplets, it is easily calculated that this ratio should be 27 for clouds at 20°C and 18 for clouds at 0°C. The ratio actually measured for the first two cloud cases (when the ground temperature was about 9°C), of about 23 is perhaps a little larger than would be expected since the cloud temperature is probably close to 0°C. This is a small discrepancy however.

The large value of attenuation measured in Case 3, i.e. during a period of heavy overcast between rainfalls, (see Fig. 2) was probably due to the fact that since precipitation occurred shortly afterwards, these clouds contained many large water droplets.[9] In this event, attenuation would be greater[10] than in the case of clouds of comparable water content which are not associated with precipitation and whose

* These ratios are estimated to be accurate to within about ±10 percent, this uncertainty being due mainly to inaccuracies in measuring the rather low values of 16-GHz attenuation (see Tables I and II).

TABLE I—SUMMARY OF CLOUD ATTENUATION MEASUREMENTS

Case Number and Type of Cloud Cover	Ground Temperature	Relative Humidity	90-GHz Atten.	Corresponding 16-GHz Atten.	Ratio $\frac{\text{90-GHz Atten.}}{\text{16-GHz}}$	Comments
1. Individual Cumulous Clouds in an otherwise clear sky	9°C	45%	Maximum: 3.7 dB Typical: 2.1 dB	0.16 dB 0.1 dB	~22	See text for note on maximum attenuation.
2. Overcast sky (no rain)	8°C	55%	Maximum: 1.6 dB	0.07 dB	~23	Signal continuously fluctuates as cloud cover moves across sky. Typical fluctuation ~1 dB at 90 GHz. No fluctuation at 16 GHz.
3. Heavily overcast sky between periods of rain (see Fig. 2)	10°C	100%	Maximum: 7.2 dB Typical: 5.2 dB	0.3 dB 0.21 dB	~24	
4. Overcast sky on cold day (no rain)	1°C	65%	Maximum: 1.64 dB	0.12 dB	~14	Most of the time there was little attenuation (<0.5 dB at 90 GHz) due to this cloud cover and no continuous fluctuations were present as in No. 2 above.

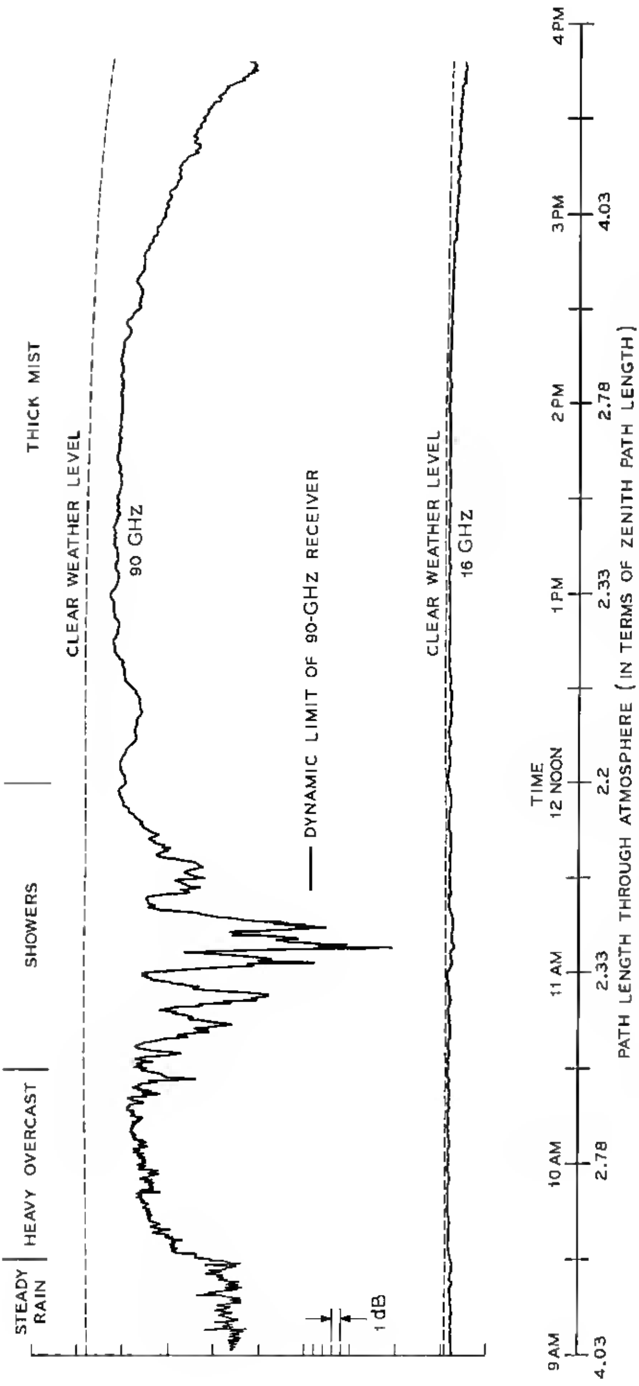

Fig. 2—Logarithmic record of 90-GHz and 16-GHz attenuation for December 8, 1969.

droplet size is very much less than a wavelength.[9] Another possibility is that part of the beam intercepted some rain; this would, of course, also have increased the attenuation.

Case 4 is different from the previous three cases because of the lower measured ratio of 90- to 16-GHz attenuation. Since the ground temperature was close to freezing during this measurement the cloud temperature was probably below −10°C. If the clouds consisted of pure ice, one would expect very little attenuation at either frequency[8] and, indeed, during much of this time, no measureable attenuation was present on either the 90- or 16-GHz channels in spite of the completely cloud-covered sky. This is in marked contrast to Case 2 when an overcast sky gave rise to continuous fluctuations of the 90-GHz signal.

On a number of occasions during the Case 4 experiment, however, some attenuation did occur, data for which are given in Table I. From what follows it seems clear that this attenuation was caused by clouds containing supercooled water droplets. Such droplets have been observed in clouds at temperatures as low as −30°C.[9]

Saxton[11] has deduced, from laboratory measurements, the dielectric properties of supercooled water at −10°C. If one substitutes these dielectric properties into Kerr's[8] expressions for attenuation due to small water droplets, an expected ratio of 90- to 16-GHz attenuation of 15 is obtained. This agrees very favorably with the measured result of 14 and suggests that clouds of supercooled droplets were indeed responsible for the attenuation experienced in Case 4.

3.2 *Excess Attenuation due to Fog*

Excess attenuation due to heavy fog was measured on one day, December 8. On this particular day attenuation due to cloud, rain and fog was measured. Figure 2 shows a copy of the logarithmic recorder outputs for both the 90- and 16-GHz channels for this data. Also shown is the clear weather signal level. It is seen from the figure that during the period of heavy fog, the signal fluctuations were much less rapid than during the period of heavy overcast. This suggests that the atmosphere was much more stable during the period of fog. Between noon and 2 P.M., the average attenuation was 3.2 dB at 90 GHz and 0.2 dB at 16 GHz, giving a ratio of 16.

If the prevailing ground temperature of 11°C is taken to be the absorbing temperature of the water droplets in the fog (since, typically, fogs do not extend very far above the ground) then from Kerr,[8] the expected ratio of 90- to 16-GHz fog absorption is calculated

to be about 24. The low measured ratio of 16 is probably due to the fact that during a fog the atmosphere is 100 percent saturated witb water vapor. Since the ratio of attenuation at 90 and 16 GHz due to water vapor in the atmosphere is about 8.5 at a ground temperature of 15°C,[12] its presence in fog will tend to lower predicted ratios of attenuation based on small droplet absorption alone.

Indeed, when one calculates the attenuation due to the extra water vapor in the atmosphere on December 8th (i.e., over the amount present when tbe clear weather level was established), and subtracts it out, values of 0.1 dB and 2.35 dB are obtained for the average attenuation, at 16 and 90 GHz respectively, due to the fog water droplets alone. This gives a value of 23.5 for tbe ratio of 16- to 90-GHz attenuation which agrees with tbe calculated value of 24.

3.3 *Excess Attenuation due to Rain*

Attenuation due to rain was measured on three days, December 8, 10, and 14. During these times, rain rates not exceeding 1 mm/bour were measured using a rain gauge located on Crawford Hill, about 400 ft. from the sun tracker.

Table II summarizes the results of the measurements of rain attenuation. In Fig. 2, the logarithmic record for December 8, is seen the effect of attenuation due to light steady rain, between 9 and 10 A.M., and due to intermittent showers, between 10:30 A.M. and noon.

On December 10, a light rain was observed from 1:30 P.M. until 2:30 P.M. when the dynamic range (25 dB) of the 90-GHz receiver was exceeded. During this time the attenuation, both at 16 and 90 GHz, increased steadily between the limits shown in Table II and tbe dB ratio of the attenuation, fluctuating randomly between 25 and 29, had an average value of about 27.

T. S. Cbu[12] has calculated expected rain attenuations for different rain rates using a Laws-Parsons drop size distribution. From Cbu's work it is observed that as the rainfall rate increases, the ratio of attenuation at 90 and 16 GHz decreases. This can be seen in Fig. 3 where the ratio is plotted against rain rate. The decrease can be understood by first noting that in a Laws-Parsons distribution (see e.g., Chu and Hogg[13]) the average raindrop size increases with increasing rain rate. Now for each frequency there is a certain drop size which is most effective in absorbing electromagnetic radiation[13]; the higher the frequency, the smaller the most effective rain-drop size. At 16 GHz the most abundant raindrops bave a smaller size than those whicb are most effective; consequently, the increasing size in a heavier rain

TABLE II—SUMMARY OF RAIN ATTENUATION MEASUREMENTS

Date Type of Rain	90-GHz Attenuation	Corresponding 16-GHz Attenuation	Ratio $\frac{\text{90-GHz}}{\text{16-GHz}}$ Atten.	Comments
12/10: Light rain observed from 1:30 P.M. to 2:30 P.M. Between 1:30 P.M. and 3 P.M., a rainfall of 0.5 mm was measured by the Crawford Hill Rain Gauge.	Min. 5.22 dB Max. >25 dB	0.2 dB 0.9 dB	dB Ratio varied randomly between 25 ~ 29	Attenuation increased monotonically both at 16 and 90 GHz during this period.
12/14: Rain mixed with snow, turning to rain observed from 12:00 P.M. to 2 P.M. No rain gauge reading obtained as gauge was full of snow. Ground temperature, 35° to 37°F.	Min. 7.00 dB (end of rain) Max. 13.6 dB	0.3 dB 0.54 dB	Ratio decreased from 28 to about 17 and increased again to 23	The maximum 90-GHz attenuation was measured before the minimum ratio of 90/16 GHz attenuation was attained.
12/8: (a) Steady rain observed from 9 to 9:30 A.M. Rain gauge measurement ~0.8 mm/hr.	16.5 dB	0.6 dB	~27	Attenuation remained reasonably constant at both frequencies during this rain (see Fig. 2).
(b) Between 10:15 A.M. and noon, showers were observed. Total amount of rain that fell during this period (from rain gauge) was ~0.5 mm.	15 dB 20 dB 24 dB >25 dB	0.65 dB 0.75 dB 0.9 dB 1 dB	23 27 27 >25	These are the values of attenuation measured at the peak of various showers (see Fig. 2).

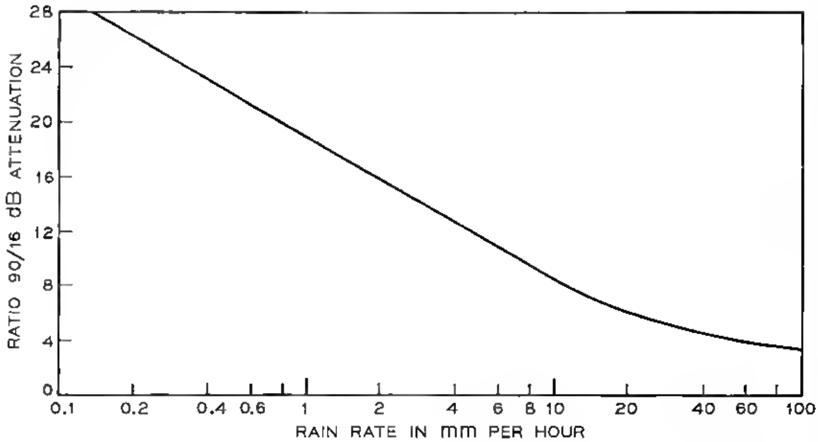

Fig. 3—Expected ratios of 90- to 16-GHz attenuation for different rain rates.

will increase the absorption effectiveness. At 90 GHz however, the most abundant drops are already larger than those which are most effective; consequently, the increasing size in a heavier rain will decrease the effectiveness.[10] The net result is to decrease the ratio of 90- to 16-GHz rain attenuation as the rain rate increases.

The observed ratio of 27 on December 10 indicates (see Fig 3) that attenuation due to a very light rain was being measured. It is interesting to note that even though the 90-GHz attenuation increased drastically during the measuring period, the ratio remained reasonably constant. This suggests that the increased attenuation was not caused by increasingly heavy rainfall at one point, but by the steadily increasing occurrence of light rain along the beam path through the atmosphere.

On December 14 the attenuation through rain mixed with snow, gradually all turning to rain, was observed. The ratio of 90- to 16-GHz attenuation showed a definite trend, beginning at a value of 28, decreasing to 17 and increasing again as the rain stopped to about 23. The maximum value of 90-GHz attenuation (13.6 dB) did not occur at the same time as the maximum value of 16-GHz attenuation (0.7 dB). The latter occurred while the ratio was at its minimum of 17 and about 10 minutes after the maximum attenuation at 90 GHz was recorded. If the effect of the snow is neglected, the above results can be interpreted, using Fig. 3, as indicating an increasing rain rate

along a decreasing path length, followed by a gradual tapering off of the rain. This is because even though the dB ratio decreased, indicating an increasing rain rate, the 90-GHz attenuation actually decreased, indicating a shorter path length through the rain. While attenuation due to snow is probably very slight at both 90 and 16 GHz,[8] its effect relative to rain is still unknown. This should be borne in mind when evaluating the above interpretation.

The data for December 8 are shown in Fig. 2 and summarized in Table II. The dB ratios are again consistant with the low measured rainfall, although it is perhaps surprising that during the showers the ratio did not decrease somewhat as one might have expected a higher rate of rainfall then.

IV. SUMMARY

Measurements of 90-GHz attenuation through the total atmosphere due to absorption by clouds, fog and rain have been presented.

Measured ratios of 90- to 16-GHz attenuation have been compared to theoretical predictions of the ratio in an effort to discover whether these predictions are reliable enough so that 90-GHz attenuation could be inferred from them. For the case of fog and cloud, this has in fact proved to be the case, provided suitable precautions are taken. In the case of rain, because of a lack of moderate or heavy rains at the sun tracker during the measuring period, it was not definitely established that the dB ratio decreased with increasing rain rate as predicted by theory, although variations in the observed values of the ratio are satisfactorily explained on this basis. However, the good agreement between theoretical and measured values of the dB ratio for the light rains encountered during the experiment make it reasonable to expect similar agreement at higher rain rates.

V. CONCLUSIONS

At 90 GHz it is seen that attenuation due to rain is the most important contributor to atmospheric extinction. This may be contrasted with the 8-14μ range where even cloud causes serious attenuation.[14] However, from the measurements given in this paper, it is seen that rain attenuation at 90 GHz is a very serious problem and that if an earth satellite communications channel is to operate in this band, sophisticated diversity schemes will have to be devised if outages are to be kept from exceeding permissable levels.

VI. ACKNOWLEDGMENTS

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